The Wave Function: It or Bit?[1]

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Abstract: Schrödinger's wave function shows many aspects of a state of incomplete knowledge or *information* ("bit"): (1) it is defined on a space of classical configurations, (2) its generic entanglement is, therefore, analogous to statistical correlations, and (3) it determines probabilites of measurement outcomes. Nonetheless, quantum superpositions (such as represented by a wave function) also define individual *physical* states ("it"). This conceptual dilemma may have its origin in the conventional *operational* foundation of physical concepts, successful in classical physics, but inappropriate in quantum theory because of the existence of mutually exclusive operations (used for the definition of concepts). In contrast, a *hypothetical realism*, based on concepts that are justified only by their universal and consistent applicability, favors the wave function as a description of (thus nonlocal) physical reality. The (conceptually local) classical world then appears as an illusion, facilitated by the phenomenon of decoherence, which is consistently *explained* by the very entanglement that must dynamically arise in a universal wave function.

[1] Draft of an invited chapter for *Science and Ultimate Reality*, a forthcoming book in honor of John Archibald Wheeler on the occasion of his 90^{th} birthday (www.templeton.org/ultimate_ reality).

1 Introduction

Does Schrödinger's wave function describe physical reality ("it" in John Wheeler's terminology [1]) or some kind of information ("bit")? The answer to this question must crucially depend on the definition of these terms. Is it therefore merely a matter of words? Not quite – I feel. Inappropriate words may be misleading, or they may even be misused in the place of lacking explanations, while reasonably chosen terms are helpful.

A *bit* is usually understood as the binary unit of information, which can be *physically realized* in (classical) computers, but also by neuronal states of having fired or not. This traditional physical (in particular, thermodynamical) realization of information ("bit from it") has proved essential in order to avoid paradoxes otherwise arising from situations related to Maxwell's demon. On the other hand, the concept of a bit has a typical quantum aspect: the very word quantum refers to discreteness, while, paradoxically, the *quantum bit* is represented by a continuum (the unit sphere in a two-dimensional Hilbert space) – more similar to an analog computer. If this quantum state describes "mere information", how can there be *real* quantum computers that are based on such superpositions of classical bits?

The problematic choice of words characterizing the nature of the wave function (or "quantum state", in general) seems to reflect the common uneasiness of physicists, including the founders of quantum theory, about its fundamental meaning. However, it may also express a certain prejudice. So let me first recall some historical developments, most of which are described in Max Jammer's informative books [2], where you will also find the relevant "classic" references that I have here omitted.

2 Historical Remarks about the Wave Function

When Schrödinger first invented the wave function, he was convinced that it describes real electrons, even though the construction of his wave equation from Hamiltonian mechanics readily led to wave mechanics on *configuration* space. As far as he applied his theory to single electron states, this had no immediate consequences. Therefore, he tried to explain the apparently observed "corpuscles" in terms of wave packets in space (such as coherent oscillator states). This attempt failed, but I will apply it to the configuration space of bounded systems in Sect. 4. Since Schrödinger firmly believed that reality must be described in space and time, he proposed nonlinear corrections to his single-electron wave equation, thus temporarily abandoning his own many-particle wave function.

When Born later proposed his probability interpretation, he initially postulated probabilities for spontaneous transitions *of a wave function into a new one*, since at this time he "was inclined to regard it [wave mechanics] as the most profound formalism of the quantum laws" (as he later explained). These new wave functions were either assumed to be plane waves (in a scattering process), or bound states (for spontaneous transitions within atoms). In both cases the final (and mostly also the initial) states were stationary eigenstates of certain subsystem Hamiltonians, which thus replaced Bohr's semi-quantized electron orbits of the hydrogen atom.[2] Born "associated" plane waves with particle momenta according to de Broglie's mysterious proposal, although this had already been incorporated into wave mechanics in the form of differential momentum operators. Only after Heisenberg had formulated his uncertainty relations did Pauli introduce the *general* interpretation of the wave function as a "probability amplitude" for particle positions *or* momenta (or functions thereof) – cf. [3]. It thus seemed to resemble a statistical distribution representing incomplete knowledge (although not about position *and* momentum). This would allow the *entanglement* contained in a many-particle wave function to be understood as statistical correlations, and the reduction of the wave function as a "normal increase of information".

However, Pauli concluded (correctly, I think, although this has also been debated) that the potentially observed classical properties (particle position or momentum) cannot be merely unknown. Instead, he later insisted [4] that "the appearance of a definite position of an electron during an observation is a *creation* outside the laws of nature" (my translation and italics). Heisenberg had even claimed that "the particle trajectory is created by our act of observing it". In accordance with Born's original ideas (and also with von Neumann's orthodox interpretation), such spontaneous "events" are thus understood dynamically (in contrast to a mere increase of information), while the process of observation or measurement is not further dynamically analyzed.

According to Heisenberg and the early Niels Bohr, these individual *events*

[2] The idea of probabilistically changing (collapsing) wave functions was generalized and formalized as applying to measurements by von Neumann in what Wigner later called the "orthodox interpretation" of quantum mechanics. (By this term he did *not* mean the Copenhagen interpretation.) These historical roots may explain why von Neumann regarded quantum jumps as the *first* kind of dynamics, while calling the Schrödinger equation a *second* "Eingriff" (intervention).

occurred in the atoms, but this assumption had soon to be abandoned because of the existence of larger quantum systems. Bohr later placed them into the irreversible detection process. Others (such as London and Bauer [5] or Wigner [6]) suggested that the ultimate events occur in the observer, or that the "Heisenberg cut", where the probability interpretation is applied in the observational chain between observer and observed, is quite arbitrary. Ulfbeck and Aage Bohr [7] recently wrote that "the click in the counter occurs out of the blue, and without an event in the source itself as a precursor to the click". Note that there would then be no particle or other real object any more that dynamically connects the source with the counter! These authors add that simultaneously with the occurrence of the click the wave function "loses its meaning". This is indeed the way the wave function is often *used* – though *not* whenever the "particle" is measured repeatedly (such as when giving rise to a track in a bubble chamber). Even if it is absorbed when being measured for the first time, the state thereafter is described by a state vector that represents the corresponding vacuum (which is evidently an individually *meaningful* quantum state).

The picture that spontaneous *events* are real, while the wave function merely describes their deterministically evolving probabilities (as Born formulated it) became general quantum folklore. It *could* represent an objective description if these events were consistently described by a fundamental stochastic process "in nature" – for example in terms of stochastic electron trajectories. A physical state at time t_0 would then *incompletely* determine that at another time t_1, say. The former could be said to contain "incomplete information" about the latter in an objective dynamical sense (in contrast to Heisenberg's concept of actual "human knowledge", or information that is processed in a computer). This indeterminism would be described by the spreading of a probability distribution, representing the decay of "objective information", contained in an initial state, about the later state. Unfortunately, this dynamical interpretation fails. For example, it would be in conflict with Wheeler's delayed choice experiments [8]. Therefore, there have been attempts to reduce the concept of trajectories to that of "consistent histories" (*partially* defined trajectories) [9]. Roughly, these histories consist of successions of discrete stochastic events that occur in situations being equivalent to the aforementioned "counters". However, what circumstances let a physical system qualify as a counter in this sense?

Can something that *affects* real events, or that keeps solid bodies from collapsing, itself be unreal? In principle, this is indeed a matter of definition. For example, electromagnetic fields were originally regarded as abstract auxiliary concepts, merely useful to calculate forces between the ("really existing") charged elements of matter. Bohm's theory demonstrates that electron trajectories *can* be consistently *assumed* to exist, and even to be deterministic under the guidance of a global wave function. Their unpredictability would be due to unknown (and unknowable) initial conditions. John Bell [10] argued that the assumed global wave function would then have to be regarded as real, too: it "kicks" the electron (while it is not being kicked back in this theory). Evidently this wave function cannot *merely* represent a statistical ensemble, although it dynamically *determines* an ensemble of potential events (of which but one is supposed to *become* real in each case – note the presumed direction of time!).

In particular, any entanglement of the wave function is *transformed* into statistical correlations whenever (local) events are known to *occur*. Even when Schrödinger [11] later called entanglement the greatest mystery of quantum theory, he used the insufficient phrase "probability relations in separated systems" in the title to his important paper. In the same year, Einstein, Podolski and Rosen concluded, also by using entangled states, that quantum theory must be incomplete. The importance of entanglement for the (real!) binding energy of the Helium atom was well known by then, total angular momentum eigenstates were known to require superpositions of product states, while von Neumann, in his book, had discussed the specific entanglement that arises from quantum measurements. Nonetheless, none of these great physicists was ready to dismiss the condition that reality must be local (that is, defined in space and time). It is this requirement that led Niels Bohr to abandon microscopic reality completely (while he preserved this concept for the classical realm of events).

3 The Reality of Superpositions

However, there seems to be more to the wave function than its statistical and dynamical aspects. Dirac's general *kinematical* concept of "quantum states" (described by his ket vectors in Hilbert space) is based on the superposition principle. It requires, for example, that the superposition of spin-up and spin-down defines a new *individual* physical state, and does not just lead to interference fringes in the statistics of certain events. For every such superposed spinor state of a neutron, say, there exists a certain orientation of a Stern-Gerlach device, such that the path of the neutron can be *predicted with certainty* (to use an argument from Einstein, Podolski and Rosen).

This spinor cannot be described as a vector with two unknown components. Other spin states would have to be *created* from the present one in other measurements (outside the laws of nature according to Pauli).

Superpositions of a neutron and a proton in the isotopic spin formalism are formally analogous to spin, although the SU(2) symmetry is dynamically broken in this case. As these superpositions do not occur in nature as free nucleons (they may form quasi-particles within nuclei), the validity of the superposition principle has been restricted by postulating a "charge superselection rule". We can now *explain* the non-occurrence of these and many other conceivable but never observed superpositions by means of decoherence, while *neutral* particles, such as K mesons and their antiparticles, or various kinds of neutrinos, *can* be superposed to form new bosons or fermions, respectively, with novel individual and observable properties.

Two-state superpositions *in space* can be formed from partial waves which escape from two slits of a screen. Since these partial waves can hardly be exactly re-focussed on to the same point, we have to rely on statistical interference experiments (using the probability interpretation) to demonstrate the existence of this superposition of single-particle wave functions. (The required *series* of events, or sets of spots on a photographic plate, have quantum mechanically to be described by tensor products – not by ensembles.) *General* one-particle wave functions can themselves be understood as superpositions of all possible "particle" positions (space points). They define "real" physical properties, such as energy, momentum, or angular momentum, only as a nonlocal whole.

Superpositions of different particle numbers form another important application of this basic principle, important for characterizing "field" states. If free fields are treated as continua of coupled oscillators, boson numbers appear as the corresponding equidistant excitation modes. Their coherent superpositions (which first appeared in Schrödinger's attempt to describe corpuscles as wave packets) may represent quasi-classical fields. Conversely, *quantum* superpositions of classical fields define field functionals, that is, wave functions over a configurations space of classical field amplitudes.

These field functionals (generalized wave functions) were used by Dyson [12] to derive path integrals and Feynman diagrams for perturbation theory of QED. All particle lines in these diagrams are no more than an intuitive short hand notation for plane waves appearing in the integrals that are actually *used*. The misinterpretation of the wave function as a probability distribution for classical configurations (from which a subensemble can be "picked out" by an increase of information) is often carried over to the path integral. In particular, quantum cosmologists are using the uncertainty relations to justify an *ensemble* of initial states (an initial indeterminacy) for presumed trajectories of the universe. Everett's relative state interpretation (based on the assumption of a universal wave function) is then easily misunderstood as a many-classical-worlds interpretation. However, Heisenberg's uncertainty relations hold for *given* quantum states, and do not require their (initial, in this case) indeterminacy as well. Ensembles of quantum states would again have to be *created* from an initial superposition (outside the laws or by means of new laws), while *apparent* ensembles may form by means of decoherence [13].

Superpositions of different states that are generated from one asymmetric state by applying a symmetry group (rotations, for example) are particularly useful. They define irreducible representations (eigenstates of the corresponding Casimir operators) as new individual physical states, which give rise to various kinds of families of states or (real) "particles".

During recent decades, more and more superpositions have been confirmed to *exist* by clever experimentalists. We have learned about SQUIDs, mesoscopic Schrödinger cats, Bose condensates, and even superpositions of macroscopic currents running in opposite directions (very different from two currents canceling each other). Microscopic elements of quantum computers (which simultaneously perform different calculations in one superposition) have been successfully designed. All these superpositions may be (or must be) observed as individual physical states. Hence, their components "exist" simultaneously. They don't form ensembles representing incomplete information about the true state as long as no unpredictable events have *occurred*.

A typical example for the *appearance* of probabilistic quantum events is the decay of an unstable state by means of tunneling through a potential barrier. The decay products (which in quantum cosmology may even be whole universes) are here assumed to enter existence, or to leave the potential well, at a certain though unpredictable time. That this description is not generally applicable has been demonstrated by experiments in cavities [14], where different decay times may interfere with one another. Many narrow wave packets, approximately representing definite decay times, would indeed have to be added coherently in order to form unitarily evolving wave functions which may decay exponentially (according to a complex energy value) in a large but restricted spacetime region. This dynamical description by means of the Schrödinger equation requires furthermore that exponential tails of an exact energy eigenstate need time to form. So it excludes superluminal effects that would result (though with very small probability) if exact eigenstates were created in discontinuous quantum jumps [15].

The conventional quantization rules, which are applied in all situations where a classical theory already exists, demand that wave functions are defined as amplitudes of superpositions of all classical configurations.[3] With the exception of single-particle states, this prodedure leads directly to the infamous *nonlocal states*. Their nonlocality is very different from a (classical) *extension* in space, which would quantum mechanically be described by a *product* of local states. Only *superpositions* of such products of subsystem states may be nonlocal in the quantum mechanical sense. In order to prevent reality from being nonlocal, superpositions were therefore usually regarded as states of information – in contrast to the conclusion arrived at above. Even hypothetical "baby" or "bubble universes" are defined to *be* somewhere else *in space* – in contrast to the "many worlds" of quantum theory. However, Bell's inequality – and even more directly so its generalizations by Greenberger, Horne and Zeilinger [16] or Hardy [17] – have allowed experimentalists to demonstrate by operational means that nonlocality must be part of reality. So why not simply accept the reality of the wave function?

As mentioned above, there are *two* apparently different aspects which seem to support an interpretation of the wave function as a state of "information": the classical *configuration* space, which replaces normal space as the "stage of dynamics" (and thus leads to quantum nonlocality), and the probability interpretation. Therefore, this picture and terminology appear quite appropriate for pragmatic purposes. I am using it myself – although preferentially in quotation marks whenever questions of interpretation are discussed.

While the general superposition principle, from which nonlocality is derived, requires nonlocal *states* (that is, a *kinematical* nonlocality), most physicists seem to regard as conceivable only a dynamical nonlocality (such as Einstein's spooky action at a distance). The latter would even have to include superluminal actions. In contrast, nonlocal entanglement must already "exist" before any crucially related local but spatially separated events occur. For example, in proposed so-called quantum teleportation experiments, a nonlocal state has to be carefully prepared initially – so nothing has to

[3]Permutation symmetries and quantum statistics demonstrate that the correct basic classical states are spatial wave modes – not particles. Individual (numbered) particle positions are analogous to gauge variables.

be *ported* any more. After this preparation, the relevant state "exists but is not there" [18]. Or in similar words: the physical state is *ou topos* (at no place), although it is *not utopic* according to quantum theory. If nonlocality is thus readily described by the formalism (just taken seriously), how about the probability interpretation?

4 The Rôle of Decoherence

Most nonlocal superpositions discussed in the literature describe controllable (or usable) entanglement. This is the reason why they are being discussed. In an operationalist approach, this usable part is often exclusively *defined* as entanglement, while uncontrollable entanglement is regarded as "distortion" or "noise". However, if the Schrödinger equation is assumed to be universally valid, the wave function must contain far more entanglement (or "quantum correlations") than can ever be used [19]. In contrast to entanglement, uncontrollable noise, such as phases fluctuating in time, would *not* destroy (or rather, dislocalize) an individual superposition. It may at most wash out an interference pattern in the *statistics* of many events (cf. [20]). Therefore, entanglement, which leads to decoherence in bounded systems even for an *individual* global quantum state, has to be strictly distinguished from phase averaging in ensembles or by means of a fluctuating Hamiltonian ("dephasing").

John von Neumann discussed the entanglement arising when a quantum system is measured by an appropriate device. It leads to the consequence that the relative phases which characterize a superposition are now neither in the object nor in the apparatus, but only in their (shared) total state. This phase cannot affect measurements performed at one or the other of these two subsystems any more. The latter are then conveniently described by their reduced density matrices, which can be formally *represented by ensembles* of subsystem wave functions with certain formal probabilities. If the interaction dynamics between system and apparatus is (according to von Neumann) reasonably chosen, the resulting density matrix of the apparatus by itself can be represented by an ensemble of (not necessarily mutually orthogonal) wave packets which would describe its pointer positions with the required probabilities. Does it therefore describe such an ensemble of new wave functions, and thus explain the measurement process? That is, have the quantum jumps into these new wave functions (the unpredictable events) already occurred according to von Neumann's unitary interaction?

Clearly not. Von Neumann's model interaction, which leads to this entanglement, can in principle be reversed in order to reproduce a local superposition that depends on the initial phase relation. For a microscopic pointer variable this can be experimentally confirmed. For this reason, d'Espagnat [21] distinguished conceptually between proper mixtures (which describe ensembles) and improper mixtures (which are defined to describe entanglement with an external system). This difference is of utmost importance when the problem of measurement is being discussed. The density matrix by itself is a formal tool that is sufficient for all practical purposes which *presume* the probability interpretation and neglect the possibility of phase revivals (recoherence). Measurements by microscopic pointers can be regarded as "virtual measurements" (representing "virtual decoherence") – in close analogy to the concepts of virtual particle emission or virtual excitations. Similarly, scattering "events" cannot be treated probabilistically as far as phase relations, described by the scattering matrix, remain relevant or *usable.* Nothing can be assumed to have irreversibly happened in virtual measurements (as it would be required for real events).

The concept of a reduced density matrix is justified by the fact that all potential measurements are local, that is, described by local interactions. Classically, dynamical locality means that an object can *directly* affect the state of another one only if it *is* at the same place. However, we have seen that quantum states are at no place, in general. So what does dynamical locality *mean* in quantum theory?

This locality (which, in particular, is a prerequisite for quantum field theory) is based on an important structure that goes beyond the mere Hilbert space structure of quantum theory. It requires (1) that there is a Hilbert space *basis* consisting of local states (usually a "classical configuration space"), and (2) that the Hamiltonian is a sum or spatial integral over corresponding local operators. (The first condition may require the inclusion of gauge degrees of freedom.) For example, the configuration space of a fundamental quantum field theory is expected to consist of the totality of certain classical field configurations on three- (or more-) dimensional space, while its Hamiltonian is an integral over products of these field operators and their derivatives. This form warrants dynamical locality (in relativistic and nonrelativistic form) in spite of the nonlocal kinematics of the generic quantum states.

So let us come back to the question why events and measurement results appear actual rather than virtual. In order to answer it we must first understand the difference between reversible and irreversible (uncontrollable) entanglement. For this purpose we have to take into account the realistic environment of a quantum system. We may then convince ourselves by means of explicit estimates that a macroscopic pointer cannot avoid becoming strongly entangled with its environment through an uncontrollable avalanche of interactions, while the quantum state of a microscopic variable remains almost unaffected in most cases.

This situation has been studied in much detail in the theory of decoherence[4] [20, 22] (while many important applications still remain to be investigated – for example in chemistry). It turns out that all phase relations between macroscopically different pointer positions become irreversibly nonlocal in this way for all practical purposes and within very short times – similar to the statistical correlations that would classically arise according to Boltzmann's molecular collisions. Boltzmann's classical correlations as well as the quantum phases are then inaccessible, and irrelevant for the future evolution, while they still exist according to the assumed deterministic dynamics. If the wave function did "lose meaning", we would not have been able to *derive* decoherence from universal dynamics.

The asymmetry in time of this dissipation of correlations requires special initial conditions for the state of the universe – in quantum theory for its wave function [23]. However, in contrast to classical statistical correlations, the arising entanglement ("quantum correlation") affects the individual state: it represents a formal "plus" rather than an "or" of incomplete information.

Two conclusions have to be drawn at this point. Decoherence occurs according to the dynamical laws (the Schrödinger equation) by means of an in practice irreversible process, and precisely where events *seem* to occur, but this does *not* lead to an ensemble representing incomplete information. The improper mixture does not become a proper one. We can neither unambiguously choose a specific ensemble to "represent" the reduced density matrix, nor even the subsystem to which the latter belongs.

From a *fundamental* point of view it would, therefore, be misleading in a twofold way to refer to the wave function and the entanglement contained in it as "quantum information". This terminology would incorrectly suggest (1) the presence of a (local) reality that is incompletely described or predicted by the wave function, and (2) the irrelevance of any environmental decoherence (though experimentally confirmed [24]) for the measurement process.

[4] The concept of decoherence became known and popular through the "causal" chain Wigner-Wheeler-Zurek.

A further dynamical consequence of decoherence is essential for the pragmatic characterization of the observed classical physical world. Consider a two-state system with states $|L>$ and $|R>$ which are "continually measured" by their environment, and assume that they have exactly the same diagonal elements in a density matrix. Then this density matrix would be diagonal in any basis after complete decoherence. While a very small deviation from this degeneracy would soon resolve this deadlock, an exact equality *could* arise from an exactly symmetric initial state, $|\pm>= (|R> \pm |L>)/\sqrt{2}$. However, if we then measured $|R>$, say, a second measurement would confirm this result, while a measurement of $|+>$ (if possible) would give $|+>$ or $|->$ with equal probabilities when repeated after a short decoherence time. It is the "robustness" of a certain basis under decoherence (a "predictability sieve" in Zurek's language)) that gives rise to its classical appearance. In the case of a measurement apparatus it is called a "pointer basis".

The problem of degenerate probabilities arises also for quasi-degenerate *continua* of states. For sufficiently massive particles (or macroscopic pointers), narrow wave packets may be robust even though they do not form a basis that diagonalizes the density matrix. Their shape and size may change in spite of their essential robustness. Collective variables (such as the amplitude of a surface vibration) are adiabatically "felt" (or "measured") by the individual particles. For microscopic systems this would represent a mere dressing of the collective mode. (My original work on decoherence was indeed influenced by John Wheeler's work on collective nuclear vibrations by means of *generator coordinates* [25].) However, decoherence must be irreversible. Even the germs of all cosmic inhomogeneities were irreversibly "created" by the power of decoherence in breaking the initial homogeneity during early inflation [13]. In other cases, such as a gas, the individual molecules may decohere into narrow wave packets in space, while they do *not* give rise to quasi-trajectories because of their lacking robustness.

Nonetheless, something is still missing in the theory in order to arrive at definite events or outcomes of measurements, since the global superposition still exists according to the Schrödinger equation. The most conventional way out of this dilemma would be to postulate an appropriate collapse of the wave function as a fundamental modification of unitary dynamics. Several models have been proposed in the literature (cf. [26]). They (quite unnecessarily) attempt to mimic precisely the observed environmental decoherence. However, since superpositions have now been confirmed far in the macroscopic realm, a Heisenberg cut for the application of the collapse may be placed *anywhere* between the counter (where decoherence first occurs in the observational chain) and the observer. The definition of subsystems in the intervening medium is entirely arbitrary, while the diagonalization of their reduced density matrices (the choice of their "pointer bases") may be convenient, but is actually irrelevant for this purpose. For a given observer, a real cut may even be assumed to exist only after another observer (who is usually referred to as "Wigner's friend", since Eugene Wigner first discussed this situation in the rôle of the final observer).

It would in fact not help very much to postulate a collapse to occur somewhere in the counter. The physical systems which carry the information from the counter to the observer, including his sensorium and even his brain, must all be described by quantum mechanics. Quantum theory applies everywhere, even where decoherence allows it to be approximately replaced by stochastic dynamics in terms of quasi-classical concepts ("consistent histories"). In an important paper, Max Tegmark [27] recently estimated that neuronal networks and even smaller subsystems of the brain are strongly affected by decoherence. While this result does allow (or even requires) probabilistic quantum effects, it excludes extended controllable superpositions in the brain, which might represent some kind of quantum computing. However, postulating a probability interpretation at this point would eliminate the need for postulating it anywhere else in the observational chain. It is the (local) *classical* world that seems to be an illusion!

Nobody knows as yet where precisely (and in fact whether) consciousness may be located as the "ultimate observer system". Without any novel empirical evidence there is no way to decide where a collapse really occurs, or whether we have indeed to assume a superposition of many classical worlds – including "many minds" [28] for each observer – in accordance with a *universal* Schrödinger equation. It is sufficient for all practical purposes to know that, due to the irreversibility of decoherence, these different minds are dynamically autonomous (independent of each other) after an observation has been completed. Therefore, Tegmark's quasi-digitalization of the neuronal system (similar to the $|R, L>$ system discussed above) may even allow us to define this subjective Everett branching by means of the diagonal form of the observer subsystem density matrix.

A genuine collapse (in the counter, for example) would produce an unpredictable result (described by a *component* of the wave function prior to the collapse). The state of ignorance after a collapse with unobserved outcome is, therefore, described by the *ensemble* of all these components with corresponding probabilities. In order to reduce this ensemble by an increase of information, the observer has to interact with the detector in a quasi-classical process of observation. In the many-minds interpretation, in contrast, there is an objective process of decoherence that does *not* produce an ensemble. (The reduced density matrix resulting from decoherence can be treated for all practical purposes *as though* it represented one. This explains the *apparently observed collapse* of the wave function.) Even the superposition of the resulting many minds describes *one* quantum state of the universe. Only from a subjective (though objectivizable by entanglement) point of view would there be a transition into *one* of these many "minds" (without any intermediary ensemble in this case). This interpretation is reminiscent of Anaxagoras' doctrine, proposed to separate the *apeiron* (a state of complete symmetry): "The things that are in a single world are not parted from one another, not cut away with an axe, neither the warm from the cold nor the cold from the warm. When Mind began to set things in motion, separation took place from each thing that was being moved, and all that Mind moved was separated." (Quoted from [2], p. 482). Although according to this quantum description the rôle of "Mind" remains that of a passive (though essential) epi-phenomenon (that can never be *explained* in terms of physical conepts), we will see in the next section how Anaxagoras' "doctrine" would even apply to the concepts of motion and time themselves.

In this specific sense one might introduce the *terminology* (though not as an explanation) that the global wave function represents "quantum information". While decoherence transforms the formal "plus" of a superposition into an effective "and" (an *apparent* ensemble of new wave functions), this "and" becomes an "or" only with respect to a subjective observer. An *additional* assumption has still to be made in order to justify Born's probabilities (which are meaningful to an individual mind in the form of frequencies in *series* of measurements): one has to assume that "our" (quantum correlated) minds are located in a component of the universal wave function with non-negligible norm [29]. (Note that this is a *probable* assumption only after it has been made.) It is even conceivable that observers may not have been able to evolve at all in other branches, where Born's rules would not hold [30].

5 The Wheeler-DeWitt Wave Function

The essential lesson of decoherence is that the whole universe must be strongly entangled. This is an unavoidable consequence of quantum dynamics under realistic assumptions. In principle, we would have to know the whole wave function of the universe in order to make local predictions. Fortunately, there are useful local approximations, and most things may be neglected in most applications that are relevant for us local observers. (Very few systems, such as the hydrogen atom, are sufficiently closed and simple to allow precision tests of the theory itself.)

For example, gravity seems to be negligible in most situations, but Einstein's metric tensor defines space and time – concepts which are always relevant. Erich Joos [31] first argued that the quantized metric field is strongly decohered by matter, and may therefore usually be treated classically. However, some aspects of quantum gravity are essential from a fundamental and cosmological point of view.

General relativity (or any unified theory containing it) is invariant under reparametrization of the (physically meaningless) time coordinate t that is used to describe the dynamics of the metric tensor. This invariance requires trajectories (in the corresponding configuration space) for which the Hamiltonian vanishes. This *Hamiltonian constraint*, $H = 0$, can thus classically be understood as a conserved initial condition (a "law of the instant") for the time-dependent states. Upon quantization it assumes the form of the *Wheeler-DeWitt equation* (WDWE),

$$H\Psi = 0 \quad ,$$

as the ultimate Schrödinger equation [32]. This wave function Ψ depends on all variables of the universe (matter and geometry, or any unified fields instead). Since now $\partial_t \Psi = 0$, the static constraint is all that remains of dynamics. While the classical law of the instant is compatible with time dependent states (trajectories), time is entirely lost on a fundamental level according to the WDWE. For a wave function that describes reality, this result cannot be regarded as just formal. "Time is not primordial" [8]!

Dynamical aspects are still present, however, since the WDW wave function Ψ describes entanglement between all variables of the universe, including those representing appropriate clocks. Time dependence is thus replaced by quantum correlations [33]. Among these variables is the spatial metric ("three-geometry"), which defines time as a *many-fingered controller of motion* for matter [34] (another deep conceptual insight of John Wheeler), just as Newton's time controls motion in an absolute sense.

The general solution of this WDWE requires cosmic boundary conditions in its configuration space. They may not appear very relevant for "us", since Ψ describes the superposition of "many worlds". Surprisingly, for Friedmann type universes, this static equation is of hyperbolic type after gauge degrees of freedom have been removed: the boundary value problem becomes an initial value problem with respect to the cosmic expansion parameter a [35]. For appropriate initial conditions at $a = 0$, this allows one to deduce a cosmic arrow of time (identical with that of cosmic expansion) [23].

Since the Wheeler-DeWitt wave function represents a superposition of all three-geometries (entangled with matter), it does not describe quasi-classical histories (defined as one-dimensional successions of states, or instants). Kiefer was able to show [36] that such histories (which define space-times) can be approximately recovered by means of decoherence along WKB trajectories that arise according to a Born-Oppenheimer approximation with respect to the Planck mass. This leads to an effective time-dependent Schrödinger equation along each WKB trajectory in superspace (Wheeler's term for the configuration space of three-geometries). Complex wave functions emerge thereby from the real WDW wave function by intrinsically breaking the symmetry of the WDWE under complex conjugation (cf. Sect. 9.6 of [20]). Each WKB trajectory then describes a whole branching Everett universe for matter.

Claus Kiefer and I have been discussing the problem of timelessness with Julian Barbour (who wrote a popular book [37] about it) since the mid-eighties. Although we agree with him that time can only have emerged as an approximate concept from a "really" timeless quantum world that is described by the Wheeler-DeWitt equation, our initial approach and even our present understandings differ. While Barbour regards a *classical* general-relativistic world as time-less, Kiefer and I prefer the interpretation that timelessness is a specific quantum aspect (since there are no parametrizable trajectories in quantum theory). In classical general relativity, only *absolute* time (a preferred time parameter) is missing, while the concept of one-dimensional successions of states remains valid.

In particular, Barbour regards the *classical* configuration space (in contradistinction to the corresponding momentum space and to phase space) as a space of global actualities or "Nows". *Presuming* that time does not exist (on the basis that there is no absolute time), he then *concludes* that trajectories (of which but one would be real in conventional classical description) must be replaced by the multi-dimensional continuum of *all* potential Nows (that he calls "Platonia"). He assumes this continuum to be "dynamically" controlled by the WDWE. After furthermore presuming a probability interpretation of the WDW wave function for his global Nows (in what may be regarded as a *Bohm theory without trajectories*), he is able to show along the lines of Mott's theory of α-particle tracks (and by using Kiefer's results) that classical configurations which are considerably "off-track" (and thus without memory of an *apparent* history) are extremely improbable. Thus come memories without a history.

One might say that according to this interpretation the Wheeler-DeWitt wave function is a *multidimensional generalization of one-dimensional time* [23]. Julian Barbour does not agree with this terminology, since he insists on the complete absence of time (although this may be a matter of words). I do not like this picture too much for other reasons, since I feel that global Nows are not required, and that the symmetry between configuration space and momentum space is only dynamically – not conceptually – broken (by dynamical locality). Nonetheless, this is a neat and novel idea that I thought is worth being mentioned on this occasion.

6 That ITsy BITsy Wave Function

Reality became a problem in quantum theory when physicists desperately wanted to understand whether the electron "really" is a particle or a wave (in space). This quest aimed at no more than a *conceptually consistent description* that may have to be guessed, but would then be confirmed by all experiments. It was dismissed in the Copenhagen interpretation according to the program of complementarity (which has therefore also been called a "non-concept"). I have here neither argued for particles nor for spatial waves, but instead for Everett's (nonlocal) wave function(al). It may serve as a consistent and universal kinematical concept, and in this sense as a description of reality (that was once also supported by John Wheeler [38]). The price may appear high: a vast multitude of separately observed (and thus unobservable to us) quasi-classical universes in one huge superposition. However, similar to Everett I have no more than extrapolated those concepts which are successfully *used* by quantum physicists. If this extrapolation is valid, the price would turn into an enormous dividend of grown knowledge about an otherwise hidden reality.

The concept of reality has alternatively been based on operationalism. Its elements are then defined by means of operations (performed by what Wheeler called "observer-participators" [8]), while these operations are themselves described in non-technical "every-day" terms *in space and time.* In classical physics, this approach led successfully to physical concepts which proved consistently applicable. An example is the electric field, which was defined by means of the force on (real or hypothetical) test particles. The required operational means (apparata) could afterwards be self-consistently described by using these new concepts themselves (partial reductionism). This approach fails in quantum theory, since, for example, quantum fields would be strongly affected (decohered) by test particles.

The investigation of quantum objects thus required various, mutually incompatible, operational means. This led to incompatible (or "complementary") concepts, seemingly in conflict with a microscopic reality. Niels Bohr's ingenuity allowed him to recognize this situation very early. Unfortunately, his enormous influence (together with the dogma that the concept of reality must be confined to objects in space and time) seems to have prevented his contemporaries to *explain* it in terms of a more general (nonlocal) concept that is successfully *used* but not directly accessible by means of operations: the universal wave function. In terms of this hypothetical reality we may now understand why certain ("classical") properties are robust even when being observed, while microscopic objects may interact with mutually exclusive quasi-classical devices under the control of clever experimentalists. However, this does *not* mean that these quantum objects have to be *fundamentally* described by varying and incompatible concepts (waves or particles, for example).

If "it" (reality) is understood in the operationalist sense, while the wave function is regarded as "bit" (incomplete knowledge about the outcome of potential operations), then one or the other kind of *it* may indeed emerge *from bit* – depending on the "very conditions" of the operational situation. No question that this will remain the pragmatic language for phyicists to describe their experiments for some time to come. However, if *it* is required to be described in terms of not necessarily operationally accessible but instead universally valid concepts, then the wave function remains as the only available candidate for *it*. In this case, *bit* (information as a dynamical functional form, as usual) may emerge *from it*, provided an appropriate (though as yet incompletely defined) version of a psycho-physical parallelism is postulated in terms of this nonlocal *it*. If quantum theory appears as a "smokey dragon" [8], the dragon itself may now be recognized as a universal wave function, veiled to us local beings by the "smoke" of its inherent entanglement.

However you turn it: *In the Beginning Was the Wave Function.* We may have to declare victory of the Schrödinger over the Heisenberg picture.

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